AN EXPERIMENTAL INVESTIGATION OF SPILLING BREAKERS

Prof. James H. Duncan
Department of Mechanical Engineering
University of Maryland
College Park, Maryland 20742-3035
phone: (301) 405-5260, fax: (301) 314-9477, e-mail: duncan@eng.umd.edu
Award #: N000149610474

LONG-TERM GOAL

The long term goal of this project is to elucidate the physics of mirco-scale breaking waves (less than about one meter wavelength) including the effects caused by ambient surfactants. Of particular interest are the physical processes that cause the free surface motions that are the source of radar back scatter from these breaking waves.

SCIENTIFIC OBJECTIVES

In order to achieve the above general goals, several more specific objectives must be achieved. The first objective is to develop methods of generating highly repeatable breaking waves in a wave tank as well as methods to control and measure the surfactant levels in the tank. In order to measure the flow phenomena in these breaking waves, systems capable of measuring crest profile histories at high temporal and spatial resolution and of measuring the flow field in the crest must be developed. With the above generation and measurement systems, the dynamics of the waves will be explored. In addition, the wave generation and measurement techniques can be used to provide a test bed for measurements of radar back scattering and to provide surface profile data for radar back scattering calculations. (These calculations and radar measurements are not part of the present contract.)

APPROACH

A programmable wave maker with a highly repeatable motion is used to generate the breaking waves in a moderate size wave tank (15 m long, 1.2 m wide, 1.0 m deep). Two methods of creating breakers were chosen: dispersive focusing of a packet of about ten waves (wave-packet method) and natural instability of a train of many waves (instability method).

The profile histories of the breaking crests are measured with a photographic technique that uses a laser light sheet for illumination. The light sheet is oriented along the centerline of the tank and the water is mixed with fluorescent dye. A 500-frame-per-second movie or video camera views the intersection of the water and the laser light sheet from the side; the glowing line seen in each image is the water surface at the centerline of the tank. These images are digitized and processed to obtain the wave profile history.

The flow field in the crest of the waves is measured with particle image velocimetry (PIV). In this method, the water is seeded with small particles and the motion of these particles, which are assumed to move with the flow, are measured from double exposure images of the particles in motion.

Surfactants in the wave tank are controlled with a skimming system. Water is removed with surface skimmers at one end of the tank and this water is treated in a smaller tank before being

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sent back to the wave tank. The surface conditions in the tank are measured with an in-situ Langmuir Trough and a capillary wave propagation technique.

WORK COMPLETED

Breaking wave crest profile history measurements of waves generated by both the wave-packet and instability methods have been completed in ambient conditions with a nearly clean surface. A paper has been completed describing the breakers generated by the wave-packet method. The data from the study of breakers generated by the side-band-instability method is still being processed.

Particle image velocimetry measurements of the breakers generated by wave-packet method have been completed and a paper describing these results is currently in preparation.

The in-situ Langmuir Trough is complete and has been used to characterize the surfactants in the above mentioned experiments. The capillary propagation method of characterizing the surfactants is presently under construction.

RESULTS

The profile history measurements have revealed some surprising and very interesting phenomena. All of the waves break in a qualitatively similar manner which is shown in the profile history in Figure 1. (This wave was generated by the wave-packet method.) A schematic of the wave profile is given in Figure 2. In the figure, the profiles are shown in a coordinate system fixed with respect to the crest; flow moves from left to right. Each line is a profile of the crest at a single instant in time. The overall wavelength of the breaker is about 77 cm but each profile only covers a width of 10 cm around the crest. Successive profiles were moved vertically in the plot so that they did not plot on top of each other; time increases vertically from profile to profile. As can be seen from Figure 1, the breaking process starts with an asymmetric wave profile which is steeper on the front face than on the rear face. After a short time, a bulge develops at the crest on the forward face (see profile marked by I, t = 0.0); the upstream edge of the bulge is called the toe, see Figure 2. As the process continues, the bulge grows in amplitude while the position of the toe relative to the crest remains fairly constant and capillary waves become visible upstream of the toe (profiles II and III, t = 0 .028 and 0.057, respectively). These capillary waves are also stationary relative to the crest. Between profiles III and IV (t = 0.093), the toe begins to move down the forward face of the wave. As this happens, ripples appear between the toe and the wave crest (profile V, t = 0.136). These ripples, which are initially stationary relative to the breaking wave crest, form a relatively random pattern and eventually grow in wavelength and decrease in phase speed so that they are left behind the crest (profile VI, t = 0.186). The toe eventually reaches a maximum distance from the crest and then begins to retreat. The above experimental measurements were repeated for wave packets with average frequencies ranging from 1.42 to 1.15 Hz. From these measurements it has been found that many of the geometrical characteristics of the surface profile history are independent of the wave frequency. Profile histories of breakers generated by the instability method are qualitatively similar but show more variation from wave to wave. An example is given in Figure 3.

The flow field measurements in the crest show that the motion of the toe down the front face of the wave is accompanied by rapid generation of vorticity. A sample flow field and corresponding vorticity plot is given in Figures 4 and 5. In these Figures, the wave is moving from left to right (opposite to that in Figures 1 and 2) and the velocity vectors are shown in the reference frame moving with the crest. Note the region of high shear between the underlying flow and the nearly stationary patch of fluid on the forward face. The instability of this shear layer is probably responsible for the undulations found in the free surface profiles.

IMPACT/APPLICATION

The general characteristics of the crest profile histories measured in this study have not been reported previously. This is possibly due to the fact that the entire transition to the turbulent flow takes only about 0.1 seconds and is therefore difficult to observe by eye. During this breaking process free surface structures with very well defined wavelengths have been observed on the wave crest. It is believed that these structures will be significant sources of radar back scatter.

TRANSITIONS

Profile history data has been supplied to several persons (Prof. David Lyzenga at University of Michigan, Dr. James West at Oklahoma State University, and Prof. Nadine Aubrey at New Jersey Institute of Technology) for use in radar scattering calculations. Also, the possibility of joint experiments in our wave tank has been discussed with Prof. J. Korenowski of RPI, who has developed an instrument that can measure surfactant distributions, and Dr. Andrew Jessup of University of Washington APL, who has developed an IR system from measuring water surface temperature.

RELATED PROJECTS

We are also investigating the entrainment of air bubbles by steady breaking waves. This experimental program of research is also funded by ONR (N000149610368, Program Manager Dr. Edwin P Rood).

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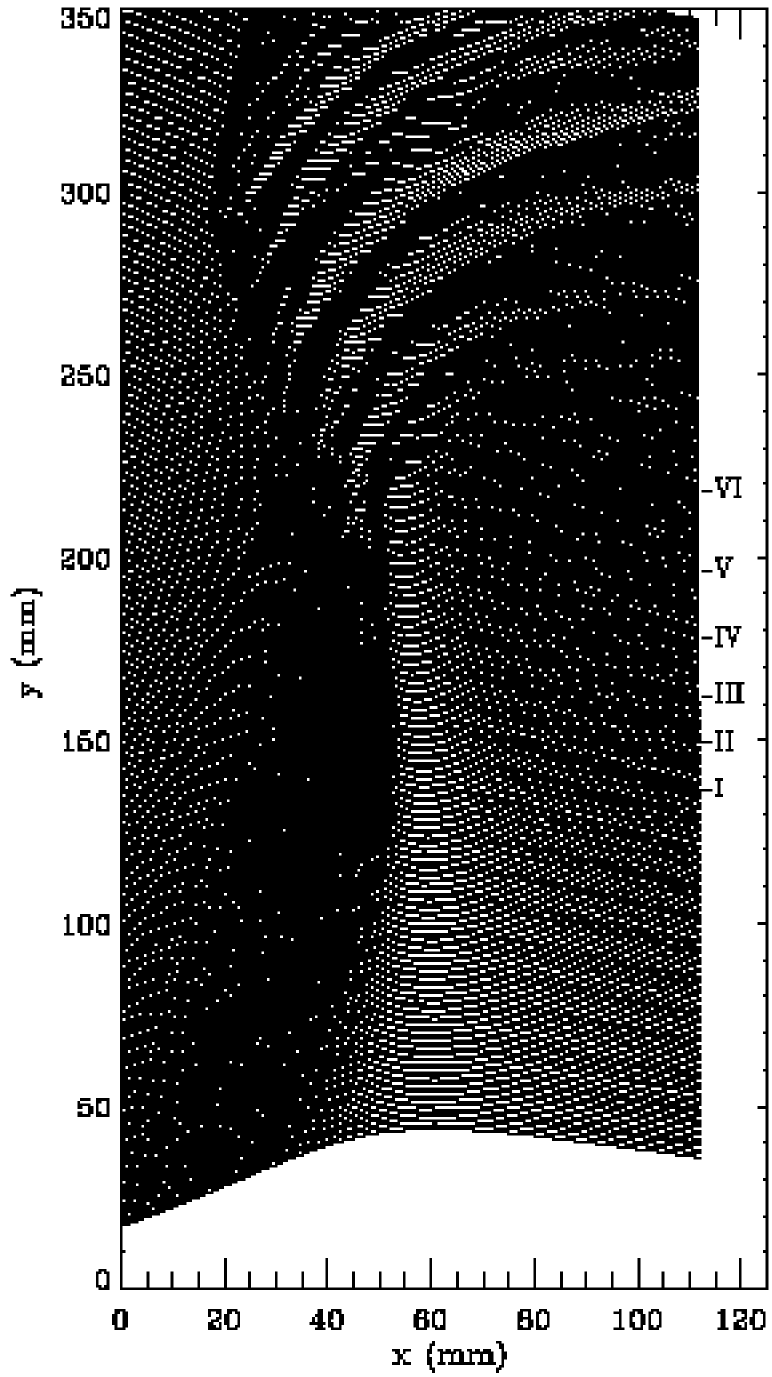

Figure 1. Profile History for a Breaking Wave Generated with the Wave-packet Method The average wave frequency is 1.42 Hz. Each successive profile is plotted 1.0 mm above the previous profile for clarity. The profiles are shown in a reference frame moving with the wave crest. In this reference frame, the mean fluid motion is from left to right. The time between profiles is 2.1 ms.

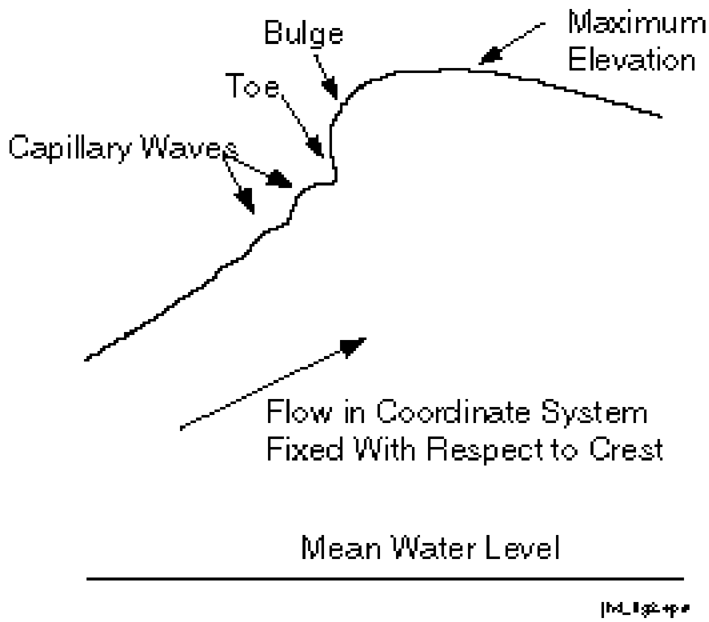

Figure 2. Schematic Showing Nomenclature for Breaking Wave Profiles

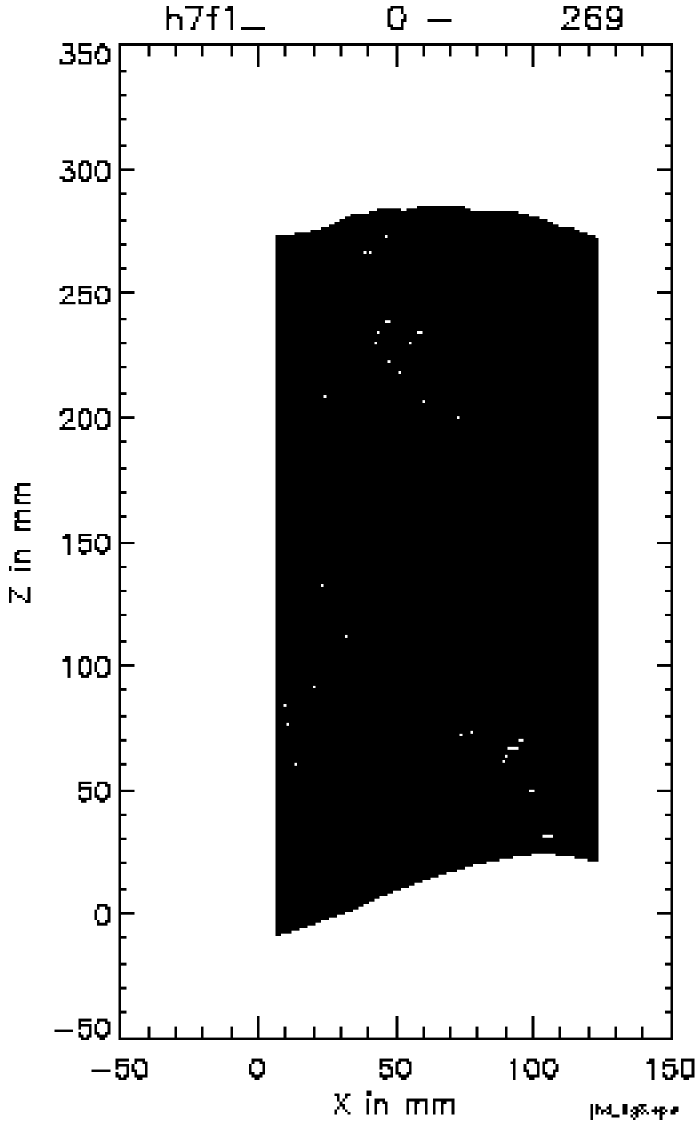

Figure 3. Profile History for a Breaking Wave Generated with the Instability Method
The average wave frequency is 1.56Hz. Each successive profile is plotted 1.0 mm above the previous profile for clarity. The profiles are shown in a reference frame moving with the wave crest. In this reference frame, the mean fluid motion is from left to right. The time between profiles is 2.1 ms.

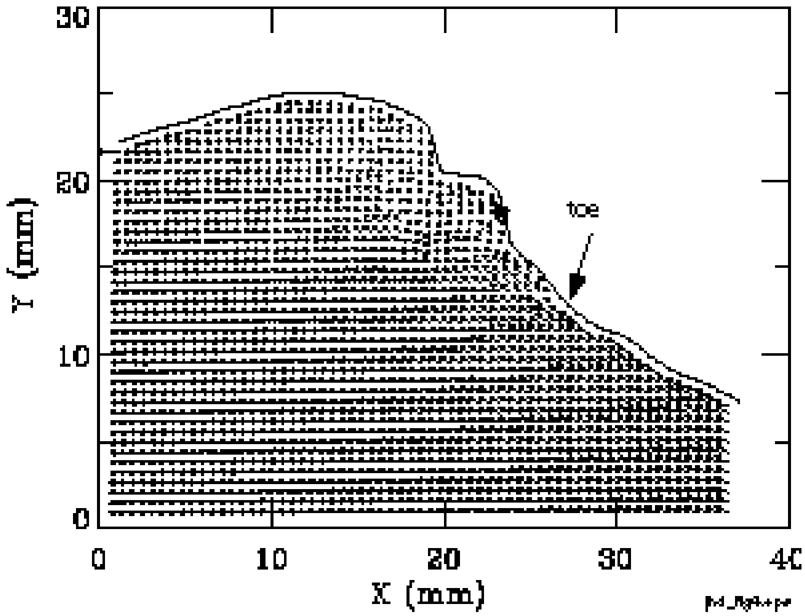

Figure 4. Velocity Field in the Crest of a Breaking Wave Generated by the Wave-Packet Method The average wave frequency is 1.42 Hz. The velocities are shown in a reference frame moving with the crest. In this reference frame the mean fluid motion is from right to left (opposite to Figures 1, 2 and 3).

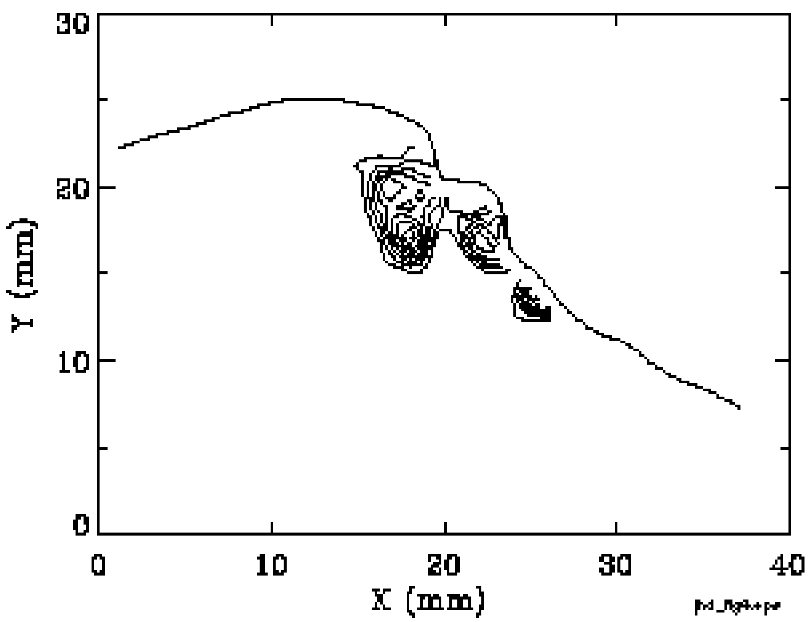

Figure 5. Vorticity Field Corresponding to Figure 5